Control system strategies for efficient liquid application of pulse width modulation (PWM) systems

by

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Abstract

Agricultural sprayers equipped with modern technologies such as pulse-width modulation (PWM) systems are widely used by farmers to efficiently use liquid application and mitigate environmental and human health concerns. These flow control systems can manage flow on a nozzle-by-nozzle basis and thus may provide uniform application pressure to maintain the uniform droplet size and target application rate. However, limited studies have been conducted which may help producers to make an informed decision in selecting a commercially available PWM system that can provide uniform spray coverage and droplet size. Therefore, two studies were conducted to 1) develop the control system strategies for the efficient liquid application for the PWM system and 2) evaluate the sensor-based variable rate nutrient application methods response to crop vigor and yield. A methodology was developed to quantify the spray coverage and droplet size uniformity of the self-propelled agricultural sprayers equipped with PWM technology during field operation. Two PWM systems, namely the John Deere ExactApply™ system (PWM1 system) and Case AIM Command Flex II™ system (PWM2 system), were operated at different combinations of frequency and duty cycle. The PWM1 system was operated 15Hz, and 30Hz, and the PWM2 system was operated at 10Hz, 15Hz, and 35%, 50%, and 75% duty cycle. To evaluate the performance of the PWM2 system at higher frequencies, the PWM2 system was operated at 10Hz, 15Hz, 20Hz, and 30Hz and at a 50% duty cycle. The results show that each PWM system provided different spray coverage uniformity when operated at different combinations of frequency and duty cycle. For the PWM1 system, the higher spray coverage, spray coverage uniformity, and droplet uniformity was achieved when the system was operated at 30Hz regardless of the duty cycle settings. The PWM2 system provided higher spray coverage at 20Hz. However, the spray coverage

uniformity, droplet size, and droplet size uniformity were significantly the same at 20Hz and 30Hz frequencies.

Based on the first study's results, the PWM2 system was utilized to conduct sensor-based variable rate nutrient application. Two fields (Lafe's and Across from Kopfers) were selected for conducting field experiments, hereafter referred to as Field1 and Field2, respectively. Field1 had two strips (strip1 and strip2), and Field2 had a single strip (strip3) which were selected for the nutrient application. All the strips were planted with different hybrids of corn. Both fields were applied with nutrients equivalent to 100 pounds (lbs) more nitrogen (N) than the strips before the nutrient application. The other 100lbs of N equivalent nutrient (UAN32) was applied to the strips at the V6 stage. Two nutrient application methods, namely the constant rate (C.R.) and sensor-based variable rate application (VRA) were used on adjacent 18.29-mwide passes to apply the nutrient onto the strips. The Augmenta sensor and the Y-drops were mounted on the PWM system to perform the variable rate side-dress nutrient application. The application rate was set at 263.41Lha-1 (28.16 GPA) to apply the 100 lbs of N using the UAN32 fertilizer. The tissue analysis was performed to measure the total %N of the crop within each small strip at the V6 stage and silking (R1) stage using the dry combustion method. The aerial imagery was taken using the Micasense Rededge camera at the R1 stage to generate the NDRE maps to analyze the crop vigor of the strips. The results showed at the V6 stage, all the strips and the control contained the total %N within the range of 3.12-3.67%, and at the R1 stage, the total %N was significantly the same for C.R. and VRA but was lower for the control. Sensor-based VRA provided greater crop vigor (NDRE: 0.6239, 0.6535, 0.6584) when compared to the constant rate (NDRE: 0.6142, 0.6287, 0.6402) for strip1, strip2, and strip3, respectively. The crop yield for the VRA was 202.84 and 189.33 bushels per acre (bu.ac$^{-1)}$, which was significantly higher than the C.R. application having crop yield of 196.17 and 182.14 $bu.ac^{-1}$ (p-value:0.0145 & 0.0146) for strip1 and strip2, respectively. For strip3, the crop yield was significantly the same for the VRA (199.74 $bu.ac^{-1}$) and C.R. application (194.0 $bu.ac^{-1}$).

In conclusion, crop producers can operate the system at higher frequencies to achieve better spray coverage and droplet size uniformity. The producers could use sensor-based variable rate nutrient application to achieve greater crop vigor and yield. However, the operators should understand the PWM system components and the control system strategies for properly utilizing the technology to reduce off-target liquid application and improve crop yield and vigor. Future research and development may include the actual chemical spraying on the crops to validate the uniformity of spray coverage and droplet size by quantifying the effectiveness of weed/pest control. Additional future studies also need to be conducted to quantify real-time nutrient flow rates on the nozzle-by-nozzle control for the sensor-based variable rate nutrient application.

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Chapter 1 - Introduction

The global population is estimated to reach from 8.0 billion in 2022 to around 9.7 billion by 2050 (United Nations, 2022). This projection will increase the demand for food, fiber, feed, and energy. To meet this demand, farmers must find efficient ways to increase crop production and substantially reduce production costs. The productivity of agricultural crops has been negatively impacted by biological (insects, pests, weeds) and environmental factors (soil fertility, climatic conditions). Farmers use pesticides to protect crops from insects, pests, and weeds and increase crop yields. Around 6 billion pounds of pesticides were used globally. In comparison, the U.S used about 1.1 billion pounds of pesticides annually in 2011 and 2012 (Figure 1.1), with herbicides making up about 50% and 60% of that amount in 2011 and 2012, respectively (Atwood et al., 2017). The U.S farmers used around 44 billion pounds of fertilizer in 2015 (USDA, 2019).

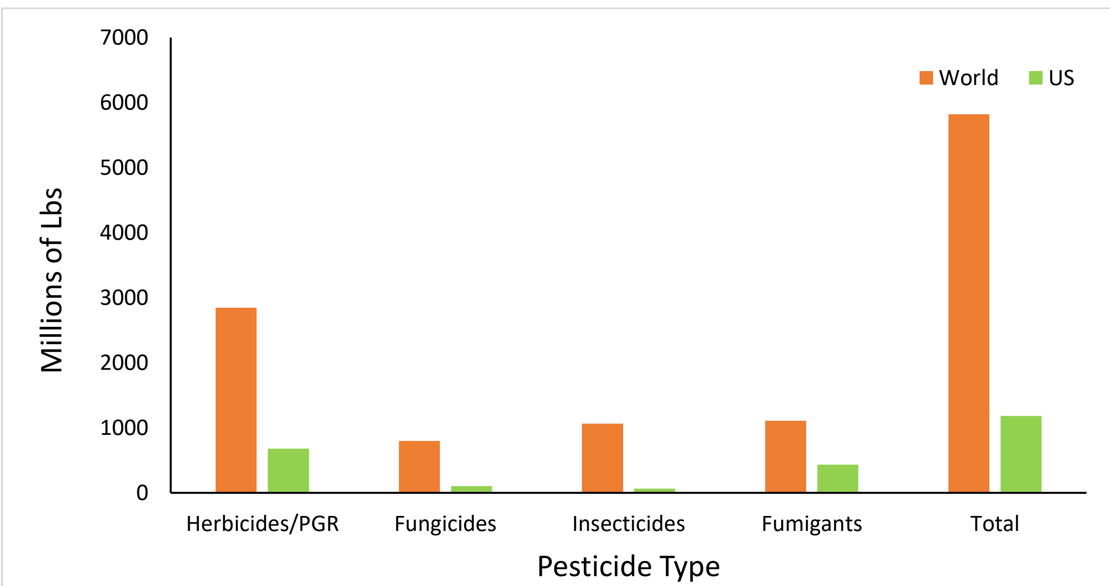


Figure 1.1 World and U.S pesticide application in 2012 by pesticide type (Atwood et al., 2017)

Pesticides have several advantages, including greater food production and a decline in insect-borne diseases. The adequate use of fertilizers helps provide sufficient nutrients to the soil/crops, eventually providing good quality crops and higher crop yields. However, the chemical application is highly scrutinized because of its impact on human health and the environment (Sharda et al., 2016; WHO-UN, 1990). Chemical applications cause environmental concerns by producing volatile organic compounds (VOC). Also, they are resistant to degradation and, therefore, may enter waterways through surface runoff and contaminate groundwater due to deep percolation (Kuivila et al., 1995; Brady et al., 2006; Werner et al., 2004). Several pest species also developed resistance to agricultural chemicals, making them hard to control (CropLife International, 2018; Heap, 2018). Therefore, it is crucial to assess the effectiveness of how these chemicals were applied, considering the system selection and the chemical application methods.

Agricultural sprayers have become more efficient in applying chemicals due to technological advancements in computers, sensors, and actuators. Agricultural sprayers vary in size, type, and control systems. In the United States, farmers commonly use the pull-behind type and self-propelled sprayers to conduct the chemical application (Figure 1.2). These sprayers use flow-based liquid control systems or pulse width modulation (PWM) technology to manage the application rate

(a) (b)

Figure 1.2(a) Self-propelled and (b) Pulled-type agricultural sprayer

The flow-based system mainly consists of a tank, pump, flow meter, groundspeed sensor, and a servo valve with a controller to apply the desired application rate (Figure 1.3). The flow-based control system regulates the flow rate, which is maintained by opening or closing the servo valve based on the operating speed, application rate, and swath width. The flow-based systems are easier to manage as compared to pressure-based systems. On the other hand, the flow-based system causes application pressure variation during the field operation, which causes the change in nozzle output, leading to the off-target application. This results in spray droplet size variability and potential issues with drift. Some systems will alert the operator if the pressure deviates from the nozzle's optimum operating range. The driver can change the speed of the vehicle to bring the pressure back within an acceptable range.

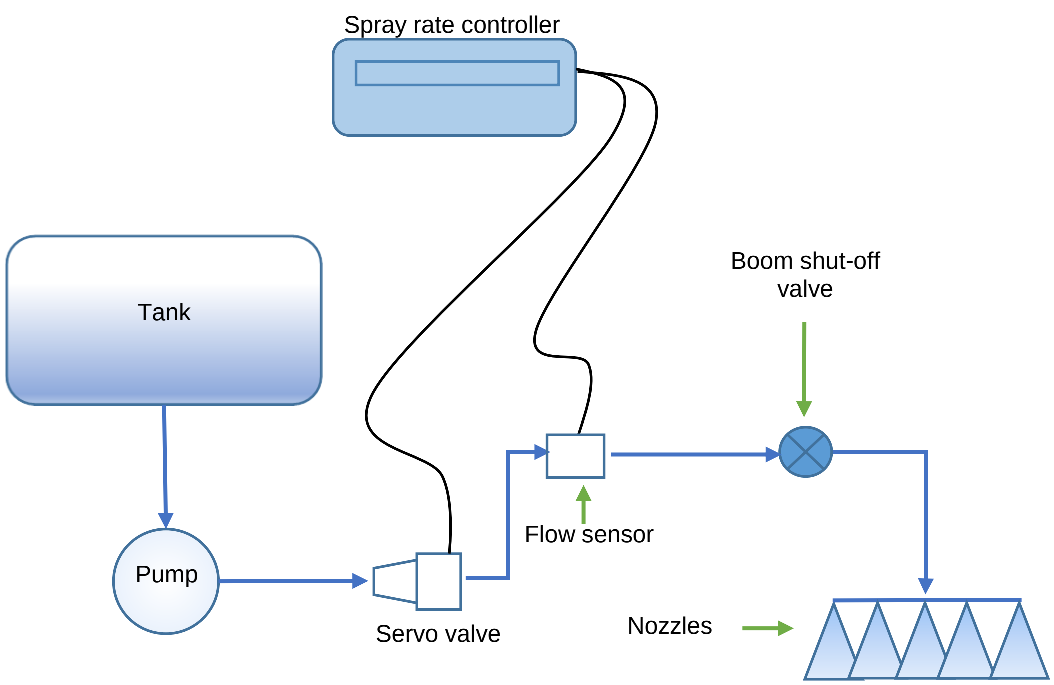


Figure 1.3 Flow-based control system of application rate

The pulse width modulation system has the ability to provide a uniform application pressure during operation, which is critical in maintaining the target application rate and droplet size (Fabula et al., 2021; Mangus et al., 2017). The product flow in a PWM system is regulated by adjusting the opening and closing of the solenoid valves. The PWM system mainly works on two major components: a duty cycle and system frequency. The duty cycle is the percent time the signal is in an ON or HIGH state for a complete cycle, and the frequency (Hz) is the number of cycles completed per second. The nozzle period is controlled by a digital signal in the ON-state (high with 12V DC input) and OFF-state (low with 0 V DC). For example, the system frequency of 10Hz means that the system operates at a 100ms cycle or ten cycles per second to operate the solenoids fixed with each nozzle, and a duty cycle of 80% means that the solenoids are in an ON state for 80ms and in the OFF state for 20ms over the 100ms cycle period. In the PWM system, each nozzle is controlled by a solenoid providing individual nozzle control capability, which aids in implementing the right duty cycle at varying nozzle speeds and application rates during straight and curved passes. The duty cycle in a PWM system influences the droplet size distribution (Butts et al., 2019). PWM systems can also be used for nutrient applications such as nitrogen application to side dress.

To ensure that these spray control technologies and nutrient application methods operate and perform as intended, they must be thoroughly examined. When using this new spray application technology, it is essential to comprehend how pressure, flow dynamics, and the control system reaction of the PWM technology affect application precision. However, no study has been conducted to provide knowledge to the producers for making a selection from currently available commercial PWM systems for uniform spray coverage and droplet size uniformity. This study will provide knowledge to the manufacturers to implement a PWM system frequency and duty cycle providing greater spray coverage uniformity. This study will not only help producers to make decisions on the purchase of the right technology but also give them the knowledge to implement the proper nutrient application methods at the right time to improve the quality of the crops, increase the crop yield, increase profits, and minimize the environmental impacts of agricultural chemicals. Therefore, the overall objective of this study aims to;

1. Develop a methodology to quantify spray coverage from a self-propelled agricultural sprayer utilizing pulse modulation spray control systems during field operation,
2. Quantify spray coverage variability when using sprayers with pulse modulation spray control systems operating at different frequencies,
3. Assess the crop vigor and yield differences when applying the nutrient using different approaches of constant rate (CR) and sensor-based variable rate application (VRA)

Chapter 2 - Spray coverage and droplet size uniformity of pulse width modulation (PWM) systems at different duty cycles and frequencies

2.1 Abstract

Correct operability and accurate spray coverage are essential to minimize off-target application and mitigate potential environmental and human health concerns in chemical applications. PWM control system can provide a uniform application pressure during operation to maintain the target application rate and droplet size. However, little knowledge exists on the impact of PWM system frequency on spray coverage uniformity. Therefore, this study was conducted to 1) develop a methodology to quantify spray coverage from a self-propelled agricultural sprayer utilizing PWM systems during field operation and 2) quantify the spray coverage, droplet size, and their uniformities when using sprayers with PWM systems operating at different frequencies. John Deere ExactApply™ system (PWM1) & Case IH AIM Command FLEX II™ system (PWM2) were operated at the frequencies of 15Hz, 30Hz, & 10Hz, 15Hz, 20Hz, 30Hz, respectively, and at 35%, 50%, and 75% duty cycles. Both sprayers have the same nozzle spacing of 0.51-m and boom height of 0.61-m above the target, thereby providing similar operating speeds for all selected duty cycles. The pressure and application rate for both systems were set at 276kPa and 10 Lha^{-1}, respectively. After spraying, the water-sensitive cards (WSCs) were collected and scanned at 600 dpi. The scanned WSCs were processed using a custom MATLAB program to assess the spray coverage & droplet size uniformity. The results showed that spray coverage uniformity from each PWM system varied with different frequencies and duty cycle combinations. The coverage uniformity results indicated that producers might consider

implementing 30Hz frequency for the PWM1 system in order to achieve greater spray coverage area (20.0%); and higher spray coverage uniformity (90.0%) and droplet uniformity (95.0%). For the PWM2 system, the producer might consider a 20Hz frequency for greater spray coverage area (17.0%). There was no significant difference between spray coverage uniformity, droplet size and droplet uniformity when operating PWM2 system at 20Hz and 30Hz. Overall, the results exhibited that greater spray coverage and droplet uniformity could be achieved when PWM spray systems were operated at frequency greater than 20Hz.

2.2 Introduction

Agriculture is heavily dependent on the application of agricultural chemicals to manage pest and increase crop production. There is also increased consciousness around use of chemicals for agricultural applications because of its impact on human health and the environment. Environmental concerns arise from production of volatile organic compounds (VOC); and surface run-off from grassed waterways to water bodies and deep percolation to reach groundwater causing non-point source pollution (Kuivila et al., 1995; Brady et al., 2006; Werner et al.,2004). More importantly, extensive use of agricultural chemicals have also resulted in several pest species developing resistance to existing chemistries, making it difficult to control pest (Croplife International, 2018; Heap, 2018).

Several innovations have been made to develop agricultural spray application technologies that can enhance the spray application accuracy of agricultural chemicals (Han et al., 2001; Lebeau et al., 2004). These technologies have become an integral component of agricultural sprayers because of their potential to minimize the number of chemicals that are being applied but to a level that is still effective in controlling pests and diseases and, at the same time, mitigate their impact on the environment (Loghavi et al., 2008). While the reduction of chemical emissions through new technologies does not have a direct economic benefit to the producers, it may, however, provide a potential benefit through product savings and better equipment productivity (Giles et al., 2011).

The use of pulse width modulation (PWM) technology in the agricultural sprayer is becoming popular because of its ability to provide a uniform application pressure during operation, which is critical in maintaining the target application rate and droplet size (Fabula et al., 2021). However, the product flow in a PWM system is regulated by adjusting the opening and closing of the solenoid valves. It makes the uniformity of the spray along the travel direction challenging to control. Previous studies show that pressure-based variable rate flow control devices have slow response time and affect nozzle performance (Giles et al., 1990; Giles et al., 2002). It was also reported that the duty cycle in a PWM system influences the droplet size distribution (Butts et al., 2019). Another factor that may influence the spray coverage during application is the boom movements. With the increase in sprayer boom widths to cover large areas, reducing the inconsistency in spray coverage becomes a critical cause of the boom movement and the frequent nozzle speed changes (Lebeau et al., 2004). A previous study shows that varying nozzle speed influenced the spray distribution along the sprayer's forward direction, resulting in under and over-application (Ooms et al., 2003).

Several companies have developed their PWM system to provide the correct amount of product, minimize losses, and reduce the impact of the chemical application on the environment. However, limited knowledge is available regarding the ability of each commercially available PWM system to provide uniform spray coverage during application. It is essential to understand the influence of the duty cycle and frequency when using a PWM system because it will affect the accuracy of product application and spray coverage. Therefore, this study was conducted to 1) develop a methodology to quantify spray coverage from a self-propelled agricultural sprayer utilizing pulse modulation spray control systems during field operation; and 2) to quantify spray coverage and droplet size uniformity when using sprayers with pulse modulation spray control systems operating at different frequencies.

2.3 Material and Methods

2.3.1 Machine set-up

This study used two 36.6-meter (m) wet boom sprayers equipped with a PWM system technology. These sprayers were the John Deere ExactApply^{TM} system (Figure 2.1(a)) & Case IH AIM Command Flex II^{TM} system (Figure 2.1(b)), hereafter referred to as PWM1 and PWM2 systems, respectively.

Figure 2.1(a). John Deere ExactApply^{TM} system

Figure 2.1(b). Case IH AIM Command Flex II^{TM} system

Figure 2.1 The two sprayers with the PWM system used in the study

For both PWM systems, the nozzles were spaced at 0.51-m and tilted at 5 degrees; the sprayer boom was set up at 0.61-m high from the target; and systems were programmed to conduct 93.54 Lha^{-1} spray application at 275.79 kPa application pressure. Water was used as a product to conduct spray application. Both systems were equipped with MR110-08 nozzles for all applications, except for the application at 30Hz frequency for PWM1 system, where two DR110-04 nozzles with equivalent droplet size and half the flow rate compared to MR110-08.

2.3.2 Experimental set-up

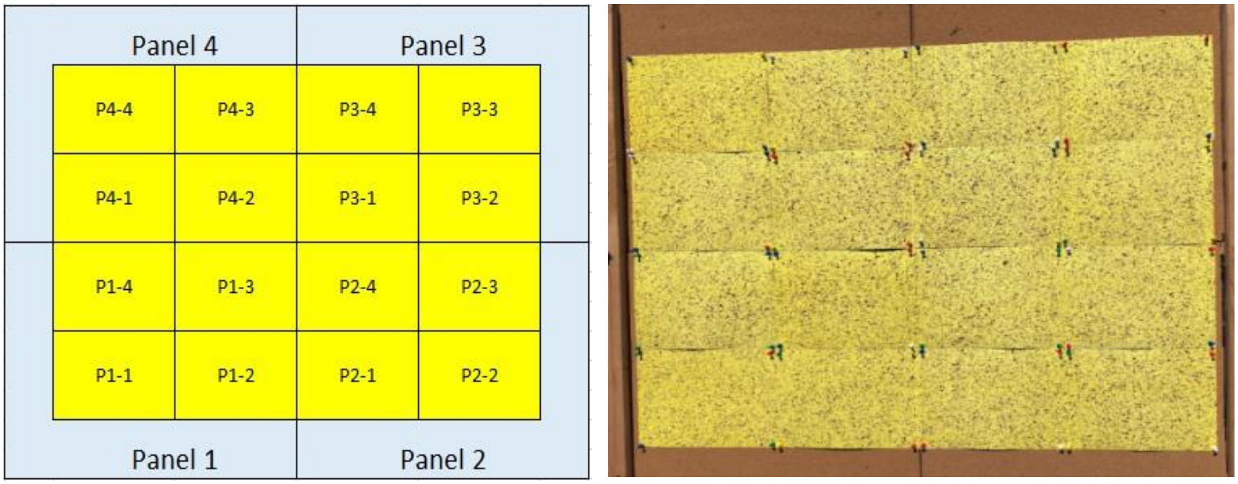
The spray coverage of the two PWM systems was evaluated using different combinations of duty cycles and frequencies. The PWM1 was operated at a frequency of 15Hz and 30Hz, while PWM2 system at 10Hz, and 15Hz, while maintaining duty cycle of 35%, 50%, and 75%. Commonly, producers operate the PWM system at their preferred duty cycle most of the time, which primarily depends on operator's choice, operator's observed performance of supplication system, operating speed, terrain, and field boundaries. Based on conversations with producers and past observations from as-applied application data, most commonly implemented duty cycle for majority of field was between 70% and 80% and lower duty cycles especially during turning were between 30% and 40%. These observations prompted the selection of duty cycle for this study.

Studies have also shown that PWM systems operating at a duty cycle shorter than 50% duty cycle resulted in application errors because of the reduced odd/even nozzle signal overlap which impacted spray coverage uniformity (Mangus et al., 2017). Therefore, to compare the system performance in terms of spray coverage and droplet size uniformity, PWM2 system was also operated at 10Hz, 15Hz, 20Hz, and 30Hz and at a duty cycle of 50%. The option of select PWM frequency beyond 15 Hz and 30 Hz was not available for PWM1 system. Although it was challenging to maintain the required duty cycle at a certain speed, the sprayer was operated to provide a duty cycle as close as possible to the desired value. The duty cycle and ground speed representations used during the test are shown in Table 2.1. Overall, nozzle spacing nozzle, nozzle type, nozzle height from target, application rate, application pressure, operating speed, and duty cycles were similar for both PWM systems during spray application.

Table 2.1 Speed and Duty cycle representations

Speed (mph)	**Duty Cycle (%)**
8	35
12	50
16	75

At least one complete cycle of the solenoid valve actuation was needed on the WSCs to analyze the spray coverage pattern. It was essential to calculate the minimum dimensions of the area covered by WSCs to get one complete cycle of application on WSCs. For this study, the minimum PWM frequency was 10Hz, and the maximum speed was 25.75 kmph. Thus, the maximum distance covered in one cycle was 0.72-m. Therefore, four panels with a dimension of 0.61-m X 0.61-m were used to get at least one complete cycle. A wooden frame was used to put all four panels together (1.22-m X 1.22m), as shown in Figure 2.2. Each panel is considered a replication, and it consists of 4 water-sensitive cards (0.24-m X 0.30-m) that were labeled to determine their location in the panel during application for ease of data analysis. All the replications were done over a single pass to reduce the effect of factors like wind speed and the dynamic deviations in boom height during operation.



(a) (b)

Figure 2.2 Panel with WSCs and indexing methodology (a), and example panel after spray application(b)

2.3.3 Data processing and analysis

All the WSCs were collected and digitized using a scanner (Epson Expression 12000 XL, Epson America, Inc. Los Alamitos, CA). Initial testing was conducted to determine the optimum resolution that was used for image processing. The WSCs were scanned at 300 dots per inch (dpi), 600 dpi, 1200 dpi, and 2400 dpi. Results showed that WSC scanned at 600 dpi, 1200 dpi, and 2400 dpi provided similar resolutions. However, WSCs scanned at 1200 dpi and 2400 dpi took a lot of time to process the image. Therefore, all the WSCs were scanned at 600 dpi and were processed to assess the spray coverage and droplet size at each PWM system setting. The scanned WSCs were processed and analyzed using a custom MATLAB program. Each WSC was divided into 48 parts using pixel values to get a ground spatial resolution (GSR) of 0.04-m X 0.04-m, and it was converted into a binary image (black and white). The white color represents the water droplets (sprayed area), and the black color represents the unsprayed area on the binary image (Figure 2.3). The percentage spray coverage area (PCA) was assessed by calculating the percentage of white color on the binary image, and the droplet size was assessed by calculating the volume-weighted mean diameter (VMD) of droplets. VMD is a parameter used to describe the average droplet size in a droplet population. VMD was calculated by using moment method (equation 1), where size of each droplet was multiplied to its corresponding volume fraction, the sum of these products was then divided to the total volume fraction of all droplets. Mathematically, VMD can be expressed as:

$$VMD(\mu m) = \frac{\Sigma(Diameter * Volume\ fraction)}{\Sigma \text{ Volume fraction}} \quad \ldots\ldots\ldots\ldots\ldots \ (1)$$

The standard deviation (SD_d) of the VMD was calculated using equation 2. The spray coverage uniformity (SCU) and droplet uniformity (DU) represent how uniform the spray coverage and droplet size are at a ground spatial resolution of 0.04-m X 0.04-m, respectively. The SCU and DU for each replication were calculated using equation 3 and equation 4, respectively.

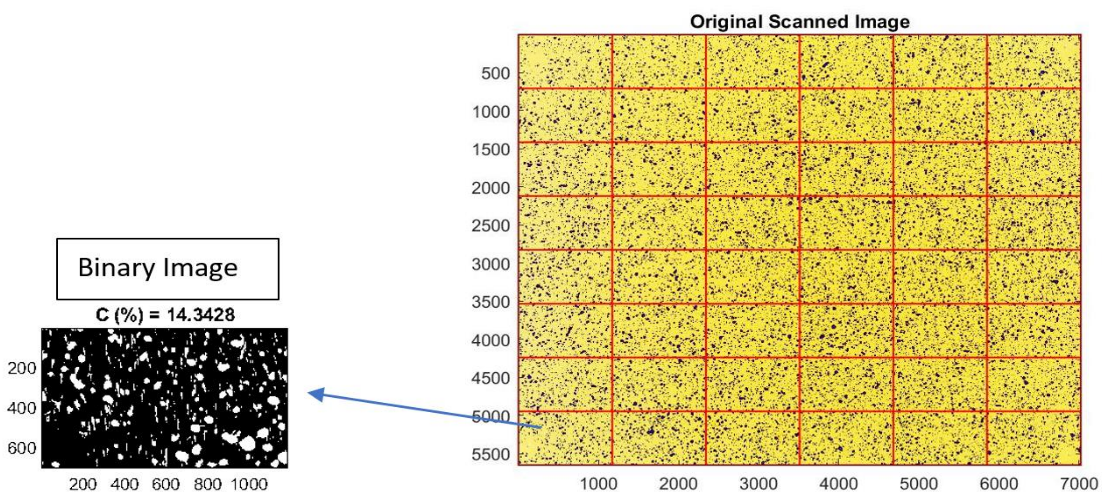
$$SD_d(\mu m) = \frac{\Sigma\left((Diameter - VMD)^2 * Volume\ fraction\right)}{\Sigma \text{ Volume fraction}} \quad \ldots\ldots\ldots\ldots\ldots \ (2)$$

$$SCU(\%) = \left(1 - \frac{SD_c}{\bar{x}_c}\right) X\ 100 \quad \ldots\ldots\ldots\ldots\ldots \ (3)$$

where SD_c is the standard deviation of spray coverage and $\bar{x}_c$ is the mean of the spray coverage.

$$DU(\%) = \left(1 - \frac{SD_d}{\bar{x}_d}\right) X\ 100 \quad \ldots\ldots\ldots\ldots\ldots(4)$$

where SD_d is the standard deviation of VMD and $\bar{x}_d$ is the mean of the VMD.



(a) (b)

Figure 2.3 Example WSC is divided into 48 parts (b) and each part converted into a binary image (a) in a custom MATLAB program for spray coverage quantification

2.3.4 Statistical analysis

For statistical analysis, a linear regression model was used on each PWM system to analyze the individual effect of frequency and duty cycle on percentage coverage area (PCA), spray coverage uniformity (SCU), volume-weighted mean diameter (VMD), and droplet uniformity (DU). The Tukey honest significant difference (HSD) test was used to check the significant difference between the different combinations of frequencies and duty cycles on the abovementioned parameters.

2.4 Results and Discussion

2.4.1 PWM1 system

The PCA, SCU, VMD, and DU of the PWM1 system that was obtained using data analysis and processing of WSCs are shown in Table 2.2. Results showed that PCA, SCU, and DU were significantly affected by the frequency, however, frequency had no significant effect on VMD. The duty cycle had no significant effect on any of the above-measured parameters. The maximum spray coverage area of 20.0% was obtained at a frequency of 30Hz, which was 17.4 -29.0% greater than when the system was operated at a 15Hz frequency. A maximum SCU value of 90.0% was observed when the system was operated at 30Hz frequency. This was approximately 1.9-5.5% higher than when the system operated at 15Hz frequency. A DU value of 95.0% was also observed when the system operates at 30Hz frequency. This value was 2.3-3.1% higher than when the system was operated at 15Hz frequency. Having a higher SCU and DU could result in better pest and disease management control by providing uniform coverage and droplet size. This may also minimize the impact of under-and over application of pesticides on the environment and may mitigate pesticide resistance among pests. However, both the duty cycle and frequency did not have a significant impact on the VMD. This could be due to the ability of the PWM system to maintain a uniform pressure that dictates the droplet size during the application, even at varying duty cycles and frequencies (Fabula et al., 2021)

Table 2.2 PCA, SCU, VMD, and DU for the PWM1 system

Frequency (Hz)	Duty Cycle (%)	PCA (%)	SCU (%)	VMD (μm)	DU (%)
15	35	17.06[b]	88.33[a][b]	818.50[a]	92.85[b][c]
	50	15.52[c]	85.29[c]	820.00[a]	92.14[c]
	75	17.06[b]	87.26[b][c]	798.75[a]	92.30[c]
30	35	18.79[a]	90.00[a]	817.28[a]	93.90[a][b]
	50	17.16[b]	88.38[a][b]	832.82[a]	93.46[b][c]
	75	20.02[a]	89.97[a]	825.44[a]	94.98[a]

[1] Means with the same letter within the columns are not significantly different at $\alpha = 0.05$

2.4.2 PWM2 system

The PCA, SCU, VMD, and DU that were obtained through data analysis and processing of WSC are shown in Table 2.3. Results of the analysis showed that varying frequencies significantly affected PCA, SCU, VMD, and DU. The duty cycle had a significant effect on PCA but had no effect on SCU, VMD, and DU. The system operated at 35% and 50% duty cycles have a greater PCA than the 75% duty cycle for both frequencies. The PCA of 18.7% was obtained at a 15Hz frequency, which was 3.3-14.1% higher than when the system operated at 10Hz. The SCU of 90.9% obtained for the system at 15Hz frequency was 5.9-6.6% more than when the system operated at 10Hz. The VMD of 828.3μm was obtained at 10Hz frequency which was 4.4-11.1% more than the system operated at 15Hz frequency. The maximum DU of 94.2% was observed when the system was operated at 15Hz frequency which was 2.1-2.5% more than the system operated at 10Hz frequency. These results showed that higher spray coverage and droplet size uniformity is expected when the PWM2 is operated at 15Hz.

The results showed that the two PWM systems (PWM1 & PWM2) performed differently when operating at different duty cycles and frequencies. Producers should be aware of the spray characteristic that a particular PWM system may provide so that they can make an informed decision on its proper operation and settings during application.

Table 2.3 PCA, SCU, VMD, and DU for the PWM2 system

Frequency (Hz)	**Duty Cycle (%)**	**PCA (%)**	**SCU (%)**	**VMD (μm)**	**DU (%)**
10	35	17.28[a][b]	85.81[b][c]	809.25[a]	92.20[b]
	50	18.07[a]	85.67[b][c]	771.11[b][c]	92.28[b]
	75	16.35[b]	85.25[c]	828.25[a]	91.91[b]
15	35	18.66[a]	89.85[a]	793.72[a][b]	94.20[a]
	50	18.16[a]	88.90[a][b]	767.31[b][c]	93.85[a]
	75	17.45[a][b]	90.85[a]	745.64[c]	94.15[a]

[1] Means that the same letter within the columns are not significantly different at $\alpha = 0.05$

2.4.3 PWM2 system operated at 10, 15, 20, and 30Hz and at 50% duty cycle

Results showed that frequency had no significant effect on PCA and DU, but significantly affected the SCU and VMD. It was found that the maximum PCA value of 17.0% was obtained at a 20Hz frequency (Table 2.4) which was 7.4% more than the system operated at a 30Hz frequency. However, the VMD, SCU, and DU were not significantly different for the system operating at

20Hz and 30Hz frequencies. The SCU and DU were minimum when the system was operated at 10Hz frequency. The results indicated that operators could expect to achieve greater spray coverage when programming the PWM2 system to operate at 20Hz and could potentially observe less wear and tear as compared operating PWM2 system at 30Hz.

Table 2.4 PCA, SCU, VMD, and DU for the PWM2 system operated at different frequencies and 50% duty cycle

Frequency (Hz)	Duty Cycle (%)	PCA (%)	SCU (%)	VMD (μm)	DU (%)
10	50	16.53[a][b]	81.13[b]	760.71[a]	90.76[a]
15	50	16.59[a][b]	85.84[a][b]	710.80[b]	92.61[a]
20	50	16.96[a]	88.86[a]	772.37[a]	93.61[a]
30	50	15.79[b]	90.01[a]	773.34[a]	94.13[a]

[1] Means that the same letter within the column are not significantly different at $\alpha = 0.05$

2.5 Conclusions

Two commercially available PWM systems were evaluated for their spray coverage and droplet size uniformity at different duty cycles and frequencies. The methodology was developed to quantify the spray coverage and droplet size uniformity. WSCs utilized during the provided desired knowledge to quantify spray coverage and droplet size uniformity when using the PWM systems at different duty cycles and frequencies. These WSCs installed on a panel provided information on the lateral and transverse coverage of the system during a complete on-off cycle of the solenoid valves. A custom MATLAB program facilitated to evaluate the spray coverage and droplet size uniformity of the PWM systems at different duty cycles and frequencies on a final ground spatial resolution. Based on the results of the field tests, the following conclusions were drawn:

1. Higher spray coverage (20.02%), spray coverage uniformity (90.0%), and droplet size uniformity (90.0%) were obtained when the PWM1 system was operated at 30 Hz regardless of duty cycle settings. Therefore, operators can opt to operate sprayers equipped with PWM1 system at a higher frequency to achieve better spray coverage and droplet size uniformity.
2. For the PWM2 system, the producer might consider operating the system at 20Hz frequency for a higher spray coverage area of 17.0%, which was 7.4% higher than coverage observed at 30Hz frequency. The spray coverage uniformity, droplet size, and droplet size uniformity were significantly the same for the system operated at 20Hz and 30Hz frequencies.
3. This study could help manufacturers implement the right PWM system frequency, providing greater spray uniformity and can help producers to make informed decisions on implementing the right technology.

Chapter 3 - Quantifying constant rate and sensor-based variable rate Nitrogen (N) fertilizer response on crop vigor and yield

3.1 Abstract

Agricultural fertilizer application is one of the essential components of crop production. It enhances crop growth, yield, and quality of the crop. An improper supply of fertilizer can potentially hamper crop growth and reduces the quality of the crop. The most widely used methods for nutrient application are the constant rate and variable rate application. However, there is a need to select the best optimum nutrient application method for proper utilization of the nutrients. Therefore, the study was conducted to (1) assess the crop vigor, the volume of nutrient (UAN32) used, and yield differences when applying the nutrient using different approaches of constant rate (CR) and sensor-based variable rate application (using Augmenta sensor) and (2) assess the potential of nutrient use variability for target yield. During this study, the Case IH AIM Command Flex II system (PWM system) was operated at 20Hz frequency for the nutrient application. The Augmenta sensor and the Y-drops were mounted on the PWM system to perform the variable rate side-dress application. Two fields (Lafe's and Across from Kopfers) were selected for conducting field experiments, hereafter referred to as Field1 and Field2, respectively. Field1 had two strips (strip1 and strip2), and Field2 had a single strip (strip3) which were selected for the nutrient application. All the strips were planted with different hybrids of corn. Both fields were applied with nutrients equivalent to 100 pounds (lbs) more nitrogen (N) than the strips before the nutrient application. The other 100 lbs of N equivalent nutrient (UAN32) was applied to the strips at the V6 stage. Two nutrient application methods, namely the constant rate (CR) and sensor-based variable rate application (VRA), were used on adjacent 60ft wide passes to apply the nutrient onto the strips. The Augmenta sensor and the Y-drops were mounted on the PWM system to perform

the variable rate side-dress nutrient application. The application rate was set at 263.41liters per hectare (Lha^{-1}) to apply the 100 lbs of N using the UAN32 fertilizer. The tissue analysis was performed to measure the total %N of the crop within each small strip at the V6 stage and silking (R1) stage using the dry combustion method. The aerial imagery was taken using the Micasense Rededge camera at the R1 stage to generate the NDRE maps to assess the crop vigor of the strips. The results showed at the V6 stage, all the strips and the control contained the total %N within the range of 3.12-3.67%, and at the R1 stage, the total %N was significantly the same for CR and VRA but was lower for the control. Sensor-based VRA provided greater crop vigor (NDRE: 0.6239, 0.6535, 0.6584) when compared to the constant rate (NDRE: 0.6142, 0.6287, 0.6402) for strip1, strip2, and strip3, respectively. The crop yield for the VRA was 202.84 and 189.33 bushels per acre ($bu.ac^{-1)}$, which was significantly higher than the CR application having crop yield of 196.17 and 182.14 $bu.ac^{-1}$ (p-value:0.0145 & 0.0146) for strip1 and strip2, respectively. For strip3, the crop yield was significantly the same for the VRA (199.74 $bu.ac^{-1}$) and CR application (194.0 $bu.ac^{-1}$). The volume of nutrients used by VRA was 13 Lha^{-1} and 3.55 Lha^{-1} less than the CR application for Field1 and Field2, respectively. The producers could use sensor-based variable rate nutrient application method to achieve greater crop vigor and yield.

3.2 Introduction

Agricultural fertilizer application is one of the essential components of crop production. The U.S farmers used around 44 billion pounds of fertilizer in 2015, among which nitrogen (N) was one of the most used fertilizers constituting about 59% of the total fertilizer consumed (USDA, 2019). Nitrogen influences crop growth, yield, and quality more than any other nutrient commonly provided as fertilizer to crops. The improper supply of N to the crop can potentially hamper the crop growth or adversely affects the environmental qualities (Schepers et al., 1991), resulting in economic losses and low use efficiency of N. Over-application of N often leads to a greater risk of groundwater contamination as a result of leaching of NO3-N (Carpenter et al. 1998) and deep percolation (Kuivila et al., 1995; Brady et al., 2006; Werner et al., 2004).

In conventional uniform rate application, the same amount of fertilizer was applied to the field. Uniform application is the main reason for low recovery rates in N fertilization and associated adverse environmental effects because of under and over-application of N in different parts of the field due to in-field spatial variability (Khosla et al., 1999; Thrikawala et al., 1999) which does not meet the spatially varying needs of the crop (Balafoutis et al., 2017; Shanahan et al., 2008). Therefore, there is a need for a site-specific crop management system for fertilizer application. Variable rate N application utilizing site-specific management zones are more economically feasible than traditional uniform N application (Koch et al., 2004) as it efficiently controls the N input to reduce input costs, increase crop yield and returns and help to protect the environment (Taylor. R & Fulton, J., 2010).

Variable rate application (VRA) has two primary technologies: Map based and sensor-based. The map-based application uses GPS, while the sensor-based application requires no GPS system. Map-based VRA requires a site-specific fertilizer application map to control the variable rate fertilizer applicator. These maps are generated by performing the systematic soil/plant sampling of the field. In soil sampling, the samples are collected from different zones of the field, which are then sent for laboratory analysis to generate site-specific maps of the soil/crop nutrient properties of interest. Specific crop/soil-based algorithms were used to develop a site-specific fertilizer application map. This method is more popular as the laboratory results are still the most trusted for determining the soil/plant properties compared to the sensor-based system. Map-based systems are perfect for collecting and interpreting data for soil properties (organic matter content and soil texture) that remain similar yearly. One of the benefits of the map-based method is the knowledge of the needed amount of nutrients for the operation before entering a field. On the other hand, the high cost of soil analysis limits the number of samples that a farmer can afford to test. Map-based soil fertility data are ineffective as soil properties like soil fertility change more rapidly due to temperature and moisture content changes.

The use of map-based systems can be eliminated with sensor-based systems. The sensor-based system measures the soil/crop properties "on the go." The measured properties are then processed and used immediately to control the variable rate applicator. A sensor-based system can collect multiple samples per acre and thus produce a more accurate depiction of in-field variability. The sensors must simultaneously respond to soil or crop properties changes to effectively accomplish the on-the-go control. There is no time delay between the measurement and application with the sensor-based systems. The major concern for the sensor-based VRA system is the capability of the sensors to respond instantaneously to changes in crop or field properties.

It is essential to determine the comparative differences in crop yield and vigor for sensor-based variable rate application compared to the system with the constant rate application. Therefore, the study was conducted to (1) assess the crop vigor, the volume of nutrient (UAN32) used, and (2) yield differences when applying the nutrient using different approaches of constant rate (CR) and sensor-based variable rate application (using Augmenta sensor).

3.3 Material and methods

3.3.1 Study Area

The study was conducted at Clay Center, Kansas, USA. Two fields (Lafe's and Across from Kopfers) were selected for conducting field experiments, hereafter referred to as Field1 and Field2, respectively. All the fields were planted using a 24-row planter head with a row-by-row spacing of 0.76-m (30-in). During the fall-winter nutrient application, 150 lbs of N was applied to the field except for the 73.15-m (240 ft) wide field strips, which were applied only with 100 lbs of N. During the planting, the fields were also supplied with nutrients equivalent to 50 lbs of N. But the strips were left in-treated for field experiments. Field1 had two strips (strip1 and strip 2), and Field2 had a single strip (strip 3), as shown in Figure 3.1. The constant rate and the sensor-based variable rate application passes were represented in green and yellow colors, respectively.

Figure 3.1 Strips in Field1 and Field2 for nutrient application

For each strip, alternate passes of constant rate (CR) and sensor-based variable rate application (VRA) treatments were done, and five blocks of around 182.88-m (600 ft) were selected for each treatment within strip1, strip2 and three blocks of 182.88-m was selected for strip3 and considered it as replications. For every strip, each treatment was implemented across

18.29-m of sprayer pass for the entire length of the strip, thereby implementing two replications of each treatment. All the strips were planted with different hybrids of corn. The strip1, strip2, and strip3 were planted with Golden Harvest 16K01, Axis 63P75, and Dekalb 65-95, respectively. A 16-row planter with 30-inch row spacing was used to establish a population of 28-30 thousand seeds per acre. All the treatments were flagged and surveyed before implementing a nutrient application for correct treatment implementation and yield quantification.

3.3.2 System Set-up

During this study, a 36.58-m boom Case IH AIM Command Flex II^{TM} system with PWM technology was used. The system was operated at a speed of 19.31 kilometers per hour (kph) and a frequency of 20Hz. The system was programmed to apply the product at 263.41 Lha^{-1}. The sprayer was also equipped with an Augmenta system and Y-drops to conduct sensor-based variable rate nutrient application (Figure 3.2).

Figure 3.2 Augmenta sensor and Y-drops mounted on the PWM system

The Augmenta system was controlled from inside the cabin by an integrated wireless Augmenta tablet. The sensor was fitted at the top cabin of the sprayer and had an 18.29-m field of view; therefore, the Y-drops were fitted at the central 18.29-m section of the boom using U-clamps and brackets. The combo adapters were used to connect the nozzles with the tubes of the Y-drops. A total of 23 Y-drops were used in this experiment. The spacing between the Y-drops was 30 inches. The orifice of 0.038 liters per second (Ls^{-1}) was used for all the nozzles except the corner nozzles, where the orifice of 0.051 Ls^{-1} was used to provide the required rate of fertilizer application. From each nozzle, the nutrient was distributed into two tubes of the Y-drops. The adjacent tubes of two different Y-drops apply the product to the same row to fulfill the amount of fertilizer needed by each row.

3.3.3 Tissue sampling

Samples were collected at two different stages of corn plant growth from each treatment within the strip (i.e. CR and VRA) and Control. Control area is the producers own practice area which is the whole field except the strips. The first sampling was done at the V6 stage just before nutrient application, where the entire portion of the plant was cut about half an inch above the soil line. A total of 15 plants from each treatment were collected at random locations and then oven dried at 60^0C for 5-7 days until the samples were totally dried. After drying, the samples were finely ground and then sent to the K-state soil testing lab for determination of plant total %N composition using dry combustion analysis. The second sampling was done at silking (R1) stage (just before the flowering stage); 15 ear leaves (first leaf below and opposite the ear) were collected at random from different plants within each treatment. The samples were then dried and sent for analysis using the same procedure done for the first sampling.

3.3.4 Nitrogen Fertilizer Application

1. Constant rate application (CR)

For CR application, the sprayer was operated on a bypass mode where the duty cycle was kept at 100%, and the application rate was set at 28.16 GPA. The system was programmed to apply the same amount of fertilizer to the whole strip. For this operation, the Augmenta system was only used to gather information on the amount of fertilizer applied to the strip.

2. Variable rate application (VRA)

During VRA, the Augmenta system consistently produces a vegetative index (AUG index) map of a field through a variety of measured parameters (Figure 3.3). AUG index map was used by Augmenta's dynamic algorithm to assess and categorize the productivity potential of different areas within each zone in a field to generate the fertilization map. The Augmenta system simultaneously communicates with the sprayer system using ISOBUS for the real-time execution of the VRA of UAN32. The system cameras also have the capability to detect rocks and waterlogged regions, which eventually reduces the amount of fertilizer applied. The fertilizer was side dressed using the Y-drops. Y-drops give workability and control to time nutrient application. It applies nitrogen at the base of the stalk, right over the root mass, for rapid and efficient uptake. No farmer action was needed during this operation as the identification of different area types was automatic and self-calibrated.

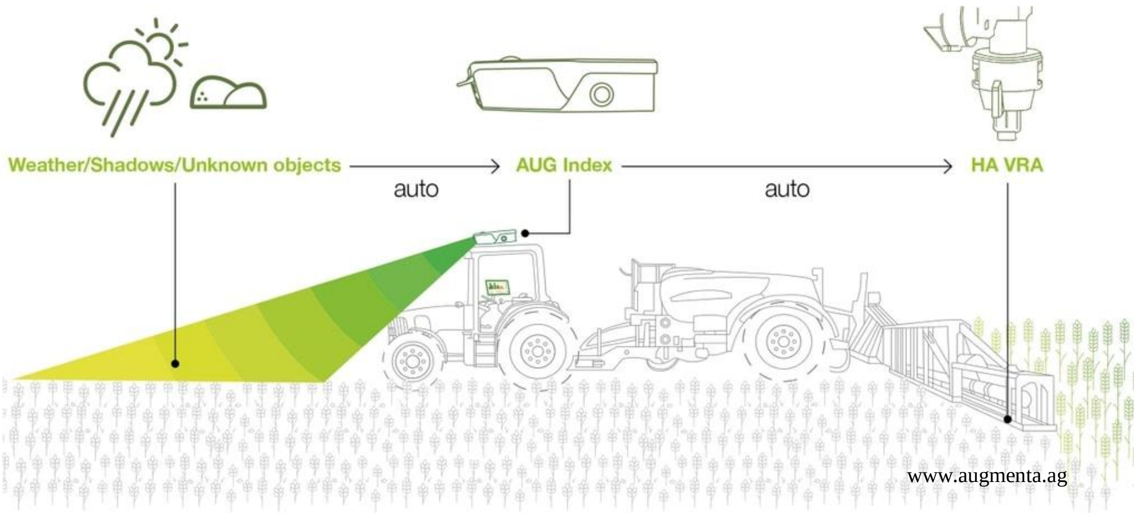


Figure 3.3 VRA application procedure using Augmenta sensor

3.3.5 Aerial imagery acquisition

The MicaSense RedEdge camera was used to capture the aerial images. The camera captures five spectral bands (Red, green, blue, red-edge, and near-infrared (NIR)) during the flight. The camera was mounted on a Matrice100 UAV, as shown in Figure 3.4.

Figure 3.4 The UAV and the camewra used for aerial imagery aquisition

The mission planning of the strips was done using a mission planner to operate the UAV at a 100m altitude with a trigger of 3sec and at 85% image overlap. The captured raw images were stored in a .jpg format and were stitched using Edgisoft software to get the required ortho-mosaic image. The ortho-mosaic image was used to get the Normalized difference red edge index (NDRE) maps for the analyses of the crop vigor variability within each application. The NDRE measures the amount of chlorophyll available in the plants. The NDRE values range from a scale of -1 to 1. The values between -1 to 0.2 refers to the developing crop or bare soil, the values ranging from 0.2 to 0.6 refers to the unhealthy or not matured crop, and the range from 0.6 to 1 indicates the healthy and mature crop.

A total of 5 ground control points (GCPs) were used for each strip to get the geo-reference of the UAS imagery, which aids in image stitching. The GCPs were made of a 0.61-m x 0.61-m wooden material and were painted black and white (Figure 3.5) to provide easy identification for the image processing software. The coordinates of the GCPs were measured using Topcon GR5, which provides a survey-grade RTK-GPS accuracy of up to 0.015-m vertical and 0.010-m horizontal.

Figure 3.5 Ground Control Point used for geo-referencing

3.3.6 Crop yield

The matured crop was harvested for each treatment individually to analyze the yield differences for each treatment for both fields. The 16-row harvester with a row spacing of 30 inches was used for the harvesting operation. For measuring the crop yield of each treatment of 24 rows individually, the crop was harvested using a 16-row pass and then an 8-row pass within the treatment, as shown in Figure 3.6. The same procedure was used to harvest all the treatments.

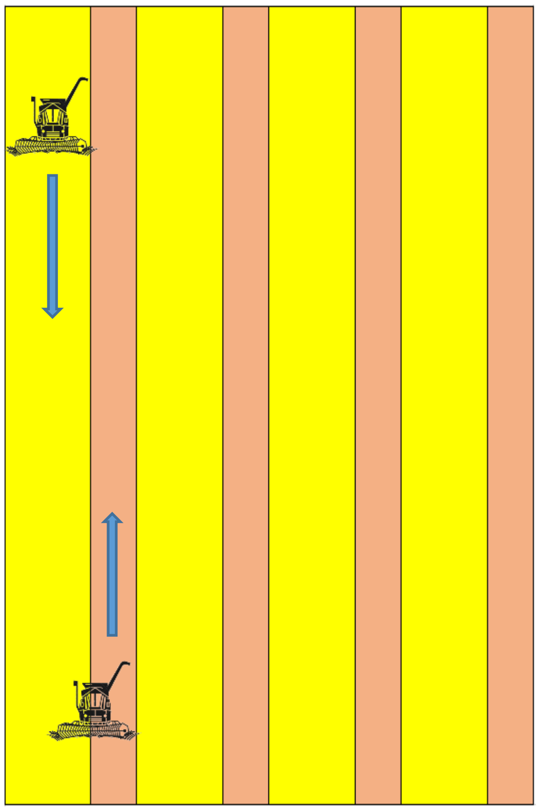


Figure 3.6 Harvesting operation within each treatment

3.4 Result and Discussion

3.4.1 Application maps

The application rates map for the VRA and CR nutrient application for each field, as shown in Figure 3.7, were obtained from the Hyper-V raven system of the PWM system. The maps were generated in ArcGIS pro software. The application rate values were used to analyze the time of occurrence within the application rate ranges. The application rate was set at 263.41 Lha^{-1} for both applications. From the results, it was analyzed that 69.79% and 90.23% of the time, the application rate was within ±10% of the target application rate for VRA and CR for Field1, respectively. For Field2, 76.95% and 79.90% of the time, the application rate was within ±10% of the target application rate for CR and VRA, respectively. The variability in the application rate that occurred during starting of the CR application for Field2 was due to the sudden changes in the speed because of the waterway passing by the strip. However, for Field1, the application rate for CR application was most of the time within the range because of fewer topographical changes within the strip

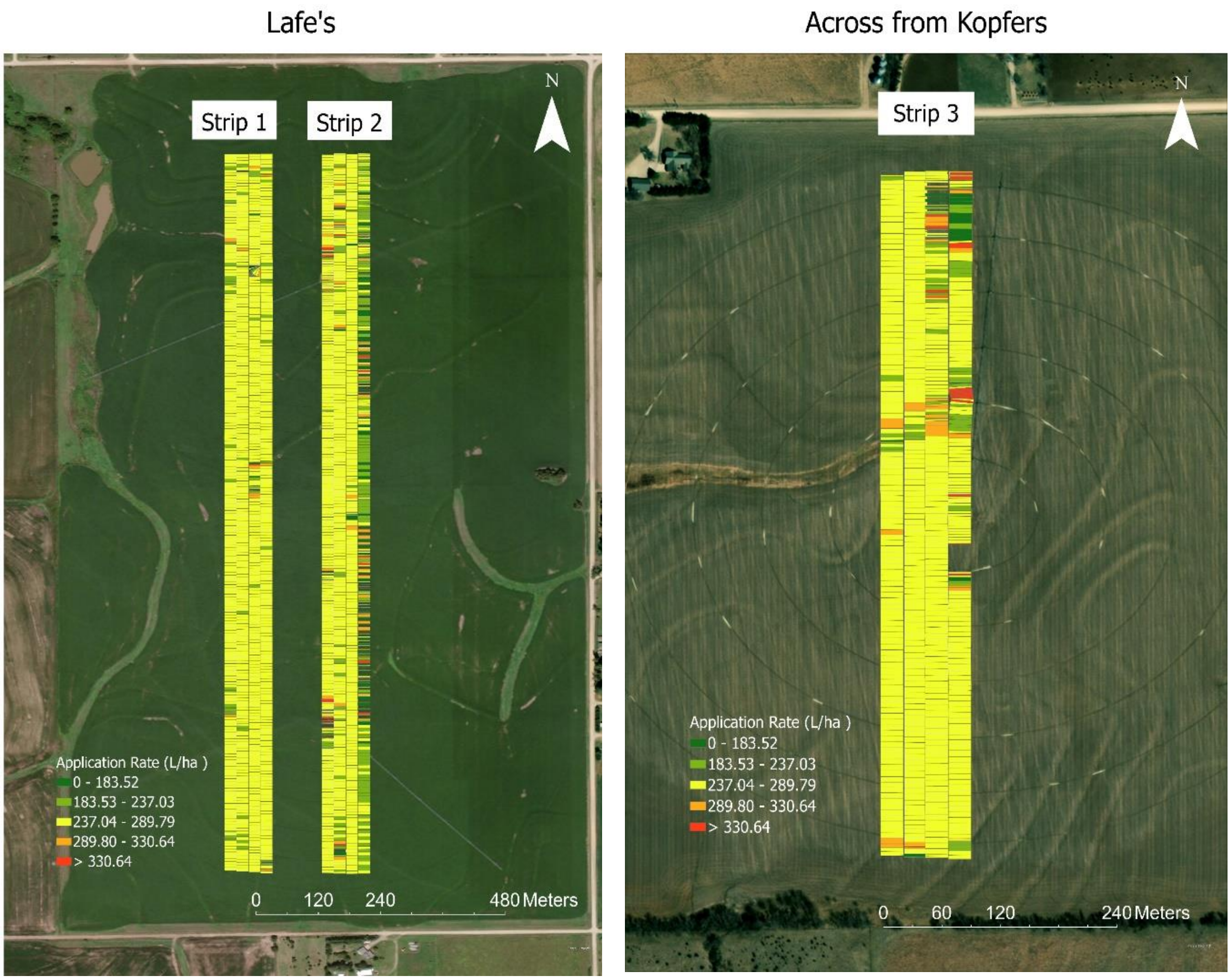


Figure 3.7 Application rate maps of the strips for Field1 and Field2

3.4.2 Comparative crop vigor under different treatments using remote sensing data

The NDRE maps, as shown in Figure 3.8, were used to assess the crop vigor for the CR and VRA application for each strip individually. The NDRE values are changing from red to green. The mean NDRE values of each block were calculated using Zonal Statistics as a Table tool in ArcGIS Pro software. The mean and the uniformity (%) of NDRE values, as shown in Table 3.1, for adjacent blocks for the two applications within the strip were analyzed to assess the comparative difference in crop vigor for each application within the strip. From the analysis, it was found that the VRA had significantly higher NDRE values as compared to the CR application for strip1, strip2, and strip3 with p-values of 0.0003, 0.0004, and 0.026, respectively. For Strip2 and strip3, the uniformity of the VRA was slightly higher than the CR application, but the uniformity of the VRA was slightly lower than the CR application for strip1. The results indicate that the user can expect healthier crops using the VRA application.

Table 3.1 NDRE values for CR and VRA application for different strips

Description	**NDRE**		**Uniformity (%)**		**Diff in NDRE (H)**	**p-value**
	CR	**VRA**	**CR**	**VRA**	**VRA - CR**	**p(H>0)**
Strip1	0.6142	0.6239	97.61	97.2	0.0097	0.0003
Strip2	0.6287	0.6535	94.34	95.92	0.0248	0.0004
Strip3	0.6402	0.6584	94.91	96.57	0.0182	0.026

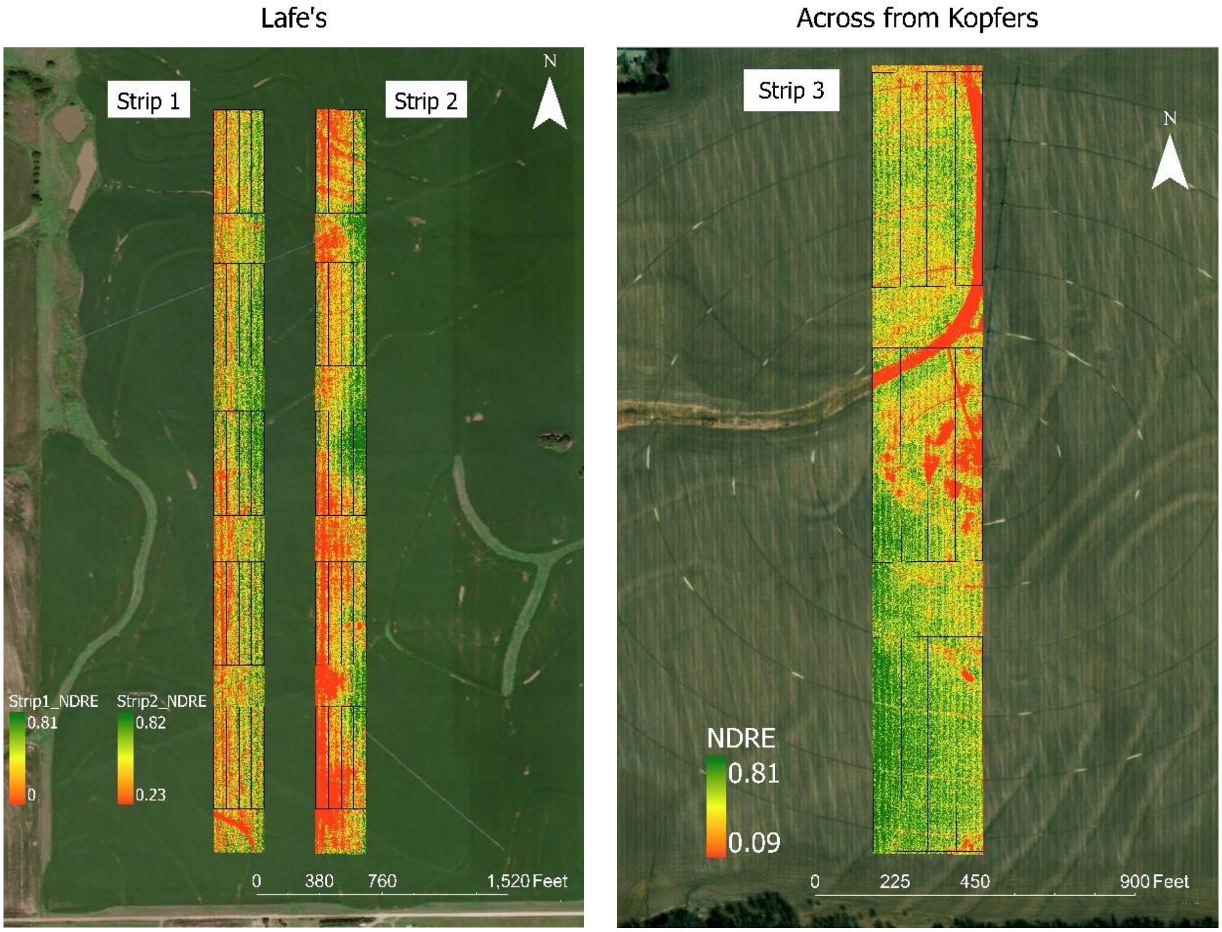


Figure 3.8 NDRE maps for different strips for (a) Lafe's and (b) Across from Kopfers field

3.4.3 Tissue sampling laboratory results for corn

The tissue sampling was done at two different stages of the corn growth, i.e., V6 and R1 stage, to calculate the total %N using the dry combustion method. The values of the total %N for each strip and application at different stages are shown in Table 3.2. The statistical test (Tukey Honest Significance Difference) was used to compare the significance of Total %N between each application. From the results obtained by tissue analyses, it was observed that the total %N was significantly the same for all the strips at the V6 stage and was in the range of 3.12 - 3.67%. At the R1 stage, the total %N for VRA and CR applications was significantly the same for all the strips. However, the total %N is lower for the Control application as compared to VRA and CR applications. Moreover, the total %N values for the strips with VRA application were quite similar

(2.70 - 2.72%). The results indicate the VRA application performed better in terms of providing the required nutrient to the crops.

Table 3.2 Tissue analysis of CR and VRA application for the strips at V6 and R1 stage

Description	Application	Total %N	
		V6 stage	R1 stage
Strip3	VRA	3.19[a]	2.7[A]
	Constant		2.56[A]
	Control	3.48[a]	2.4[B]
Lafe East	VRA	3.67[a]	2.72[A]
	Constant		2.7[A]
	Control	3.31[a]	2.3[B]
Lafe west	VRA	3.12[a]	2.72[A]
	Constant		2.49[A]
	Control	3.31[a]	2.3[B]

[1] Means that the same letter within the column is not significantly different at $\alpha = 0.05$

3.4.4 Comparative yield differences

The crop yield maps for both fields are shown in Figure 3.9, were used to assess the crop yield for the VRA and CR application within each strip. The crop yield values are extracted from the crop yield maps for each block of both applications within the strip and were used to check the comparative yield differences between both application methods. Table 3.3 shows the average crop yield, the difference in crop yield, and the p-values obtained using a statistical test (Tukey test) for each strip. The results indicate that there was a significant difference in the crop yield for VRA and CR application in strip1 and strip2. The crop yield for the VRA was 202.84 and 189.33 bushels per acre (bu.ac^{-1}), which was significantly higher than the CR application having crop yield of

196.17 and 182.14 bu.ac^{-1} (p-value:0.0145 & 0.0146) for strip1 and strip2, respectively. For strip3, the crop yield was significantly the same for the VRA (199.74 bu.ac^{-1}) and CR application (194.0 bu.ac^{-1}).

Figure 3.9 Crop yield map for (a) Lafe's and (b) Across from Kopfers field with blocks

Table 3.3 Crop yield for CR and VRA within each strip

Description	Crop Yield (bu./ ac)		Diff in yield (D)	p-value	
	CR	VRA	(VRA – CR)	p(D>0)	p(D<0)
Strip1	196.17	202.84	6.67	0.0145	X
Strip2	182.14	189.33	7.19	0.0146	X
Strip3	194	199.74	5.74	0.051	0.949

3.4.5 Estimation of nutrient savings

The results show that the VRA consumed fewer nutrients per acre as compared to the CR application. The nutrient savings was calculated by subtracting the nutrient used in VRA from the CR application. The nutrient savings was around 13 Lha^{-1} and 3.56 Lha^{-1} for Field1 and Field2, respectively. The area of Field1 and Field2 was around 116.5 and 52.61 hectares, respectively. Thus, if we perform the VRA for Field1 and Field2, we would be able to save around 1515 and 187 liters of nutrients, respectively, when compared to the CR application. However, the results cannot be generalized as the volume of nutrients required in VRA depends on the condition of the field.

Table 3.4 Application rate for CR and VRA for each field

Description		Applied app rate (Lha^{-1})	Target app rate (Lha^{-1})	Savings (Lha^{-1})
Field1	CR	261.44	263.41	13
	VRA	248.44	263.41	
Field2	CR	260.98	263.41	3.56
	VRA	257.42	263.41	

3.5 Conclusions

The difference in crop yield and crop vigor for the VRA and CR application was investigated. The tissue analysis results showed that the total %N was significantly similar for both the application and the control. At the silking (R1) stage, the total %N was similar for the VRA and the CR application and was significantly higher than the control. From the results, we can interpret that we might get a higher total %N in crops when a significant amount of the nutrient was applied at the V5-V6 stage rather than putting all the nutrients at or before the planting operation. The PWM systems were operated within ±10% of the target application rate for most of the time. The crop vigor was measured in terms of NDRE values. The VRA provided significantly higher average crop vigor with the NDRE values of 0.6239, 0.6535, 0.6584 when compared to the CR application with NDRE values of 0.6142, 0.6287, 0.6402 for strip1, strip2, and strip3, with a p-value of 0.0003, 0.0004, and 0.026, respectively. However, the uniformity in crop vigor was significantly the same for the VRA and CR application. The crop yield for the VRA was 202.84 and 189.33 $bu.ac^{-1}$, which was significantly higher than the CR application having crop yield of 196.17 and 182.14 $bu.ac^{-1}$ (p-value:0.0145 & 0.0146) for strip1 and strip2, respectively. For strip3, the crop yield was significantly the same for the VRA (199.74 $bu.ac^{-1}$) and CR application (194.0 $bu.ac^{-1}$). The results indicate that VRA might perform better than CR application for achieving comparatively higher crop yields at larger fields. Moreover, the volume of nutrients used by VRA was 13 Lha^{-1} and 3.56 Lha^{-1} less than the CR application for Field1 and Field2, respectively. The crop producers could use the sensor-based variable rate nutrient application method to achieve greater crop vigor and yield.

Chapter 4 - Conclusions

4.1 Summary of Findings

In this research, two studies were conducted to 1) develop the control system strategies for the efficient liquid application for the PWM system and 2) evaluate the sensor-based variable rate nutrient application methods response to crop vigor and yield. A methodology was developed to quantify the spray coverage and droplet size uniformity for efficient liquid application. Higher spray coverage (20.02%), spray coverage uniformity (90.0%), and droplet size uniformity (89.98%) were obtained when the PWM1 system was operated at 30 Hz regardless of duty cycle settings. For the PWM2 system, the producer might consider a 20Hz frequency for a higher spray coverage area of 16.96%, which was 7.41% more than the 30Hz frequency. The spray coverage uniformity, droplet size, and droplet size uniformity were significantly the same for the system operated at 20Hz and 30Hz frequencies.

In the second study, the application rate of the PWM system was within ±10% of the target application rate for 69.79% and 90.23% of the time for VRA and CR applications for Field1, respectively. For Field2, 76.95% and 79.90% of the time, the application rate was within ±10% of the target application rate for CR and VRA, respectively. The results showed that at the V6 stage, all the strips and the control contained the total %N within the range of 3.12-3.67%, and at the R1 stage, the total %N was significantly the same for CR and VRA but was lower for the control. Sensor-based VRA provided greater crop vigor (NDRE: 0.6239, 0.6535, 0.6584) when compared to the constant rate (NDRE: 0.6142, 0.6287, 0.6402) for strip1, strip2, and strip3, respectively. The crop yield for the VRA was 202.84 and 189.33 bushels per acre ($bu.ac^{-1}$), which was significantly higher than the CR application having crop yield of 196.17 and 182.14 $bu.ac^{-1}$ (p-value:0.0145 & 0.0146) for strip1 and strip2, respectively. For strip3, the crop yield was significantly the same for the VRA (199.74 bu.ac^{-1}) and CR application (194.0 bu.ac^{-1}). The volume of nutrients used by VRA was 13 Lha^{-1} and 3.55 Lha^{-1} less than the CR application for Field1 and Field2, respectively.

4.2 Implications

The findings of this research could help the operators to understand the PWM system components and the control system strategies for properly utilizing the technology to reduce off-target liquid application and improve crop yield and vigor. This study could help manufacturers implement the right PWM system frequency, providing greater spray uniformity and helping producers make decisions on purchasing the right technology. The crop producers could use the sensor-based variable rate application method for greater crop yield and vigor. The timing of nutrient application can also affect the availability of total %N within the crops. Applying half of the nutrients at the V6 stage of corn rather the applying the whole amount before/at the time of planting could help improving the total %N in the crops. All of these findings could help us in the efficient use of chemicals

4.3 Future work

The primary goal of this research was to develop a methodology to quantify the spray coverage and droplet size uniformity for efficient liquid application and to quantify the sensor-based variable rate application response for crop yield and vigor. Future research and development may include the actual chemical spraying on the crops to validate the uniformity of spray coverage and droplet size by quantifying the effectiveness of weed/pest control. Additional future studies also need to be conducted to quantify real-time nutrient flow rates on the nozzle-by-nozzle control for the sensor-based variable rate nutrient application.

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